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An Electrical Method of Studying Sound Waves

AN ELECTRICAL METHOD OF STUDYING SOUND WAVES

BY

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THESIS

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

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I STATEMENT OF PROBLEM

As scientific learning advances, and more is known of the laws of nature, we find that many phenomena can be explained by means of wave motion. These waves may be of various types and represent various forms of energy. There are, however, certain characteristics which are common to all.

All waves have a particular medium in which they travel. Light and X-rays are propagated in the hypothetical medium - ether. For sound waves we need introduce no hypothesis or element of questionable nature. In fact, the knowledge of the subject of sound propagation is much more definite and easily understood than many of the other waves. Sound travels in matter, the commonest case being its transmission in air.

Waves may be classified into two types, (1) those which vibrate longitudinally, and (2) those which vibrate transversely. Sound waves belong to the first class. They consist of alternate compressions and rarefactions of the medium and travel with various velocities depending on the nature of the medium.

In air the velocity of sound is about 341 meters a second at 16° Centigrade. The pitch of the sound makes no difference in the velocity for all practical purposes, although it is found that extremely loud sounds may travel at a slightly higher velocity. A change in temperature, however, causes a change of about two feet per degree per second.

Waves may also be classed according to whether they are periodic or non-periodic, that is, whether a wave of given form or a group of such waves is repeated at definite intervals of time. Sound waves which are non-periodic are perhaps the most common. These are the

sounds we call noises. Those which are periodic and are much more pleasant to the ear are known as musical tones.

Although better known for his research and laws of electrical phenomena, Ohm stated, in 1843, a law which is known as "Ohm's Law of Acoustics". This law covers the fundamentals of musical sounds very completely and includes the following statements:

(1) All musical tones are periodic.

(2) The human ear perceives pendular vibrations alone as simple tones.

(3) All varieties of tone quality are due to particular combinations of a larger or smaller number of simple tones.

(4) Every motion of the air which corresponds to a complex musical tone or to a composite mass of musical tones is capable of being analyzed into a sum of pendular vibrations, and to each simple vibration corresponds a simple tone which the ear may hear.

Thirty years later the following addition was made by Helmholtz which is also of great importance:

"The quality of a musical note depends solely on the number and relative strength of its partial simple tones and in no respect on their difference in phase."

Musical tones may be said to have the following attributes, (1) pitch, (2) intensity, and (3) quality. The pitch of a stationary source of sound is entirely dependent upon the number of vibrations per unit of time the source is producing, or, which is identical, upon the length of the wave. This relation may be shown by the expression

$$V = LN$$

where V = velocity of wave

L = length

N = frequency of vibration.

Since the velocity is constant for all pitches, it follows that the wave length is inversely proportional to the frequency.

There are limits, however, to the sounds which the ear can perceive. These vary greatly in different individuals, the average limits being between 30 and 30,000 vibrations per second.

Intensity is an indication of the energy of the sound. It is dependent upon the frequency as well as the amplitude of vibration and is expressed by the equation

$$I = n^2 A^2$$

where I = intensity or energy of a simple vibratory motion

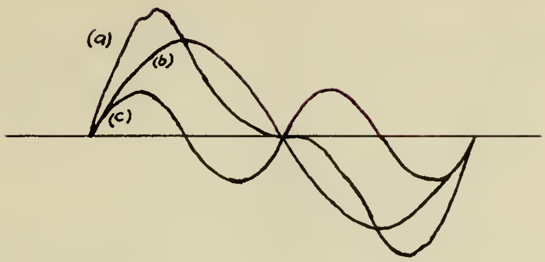
A = amplitude

n = frequency.

Quality, the third attribute, is that by which we distinguish the sound made by one source from another. It is this which differentiates the tone of a violin from that of a cornet, although a note of the same pitch and intensity be sounded on each. This is due to overtones which sound with a different pitch and intensity than the fundamentals. If these overtones are even multiples of the fundamentals they are called harmonics.

As Ohm's law states, these harmonics are heard by the ear as separate simple tones. If the wave be photographed by any means, we find not the separate harmonics at various frequencies but a single wave in which the effects of the various harmonic components are added.

A simple tone has what is mathematically known as a sine wave, i.e., one produced by simple harmonic motion.



In the above figure is shown a wave (a) which is the resultant of the two waves, (b) and (c) having the frequency n and 2n. Now in photographing waves by the method described in the next chapter (a) is the one obtained. To study the quality the wave must be broken down or analyzed into the sum of waves of which it is composed.

A mathematical expression of statement (4) of Ohm's law is found in Fourier's Series.

$$y = a_0 + a_1 \sin \theta + a_2 \sin 2\theta + \ldots\ldots a_k \sin k\theta + \ldots\ldots$$
$$+ b_1 \cos \theta + b_2 \cos 2\theta + \ldots\ldots b_k \cos k\theta + \ldots\ldots$$

which may be expressed as follows:

$$y = A_1 + C_1 \sin(\theta+\alpha_1) + C_2 \sin(2\theta+\alpha_2) + \ldots\ldots C_n \sin(n\theta+\alpha_n) + \ldots\ldots$$

where C_1, C_2, ... C_n are the maximum values of the fundamental, first, second, ... n-1 harmonics. Since from Helmholtz's statement we find that the phase difference of the various harmonics is of no importance in studying quality, the angle α need not be considered. The ratio of the values of the constants, therefore, indicate the relative strength of the harmonics.

In this thesis no attempt has been made to study any sounds other than musical tones. These have been confined to the quality

of the waves of a few instruments and voice.

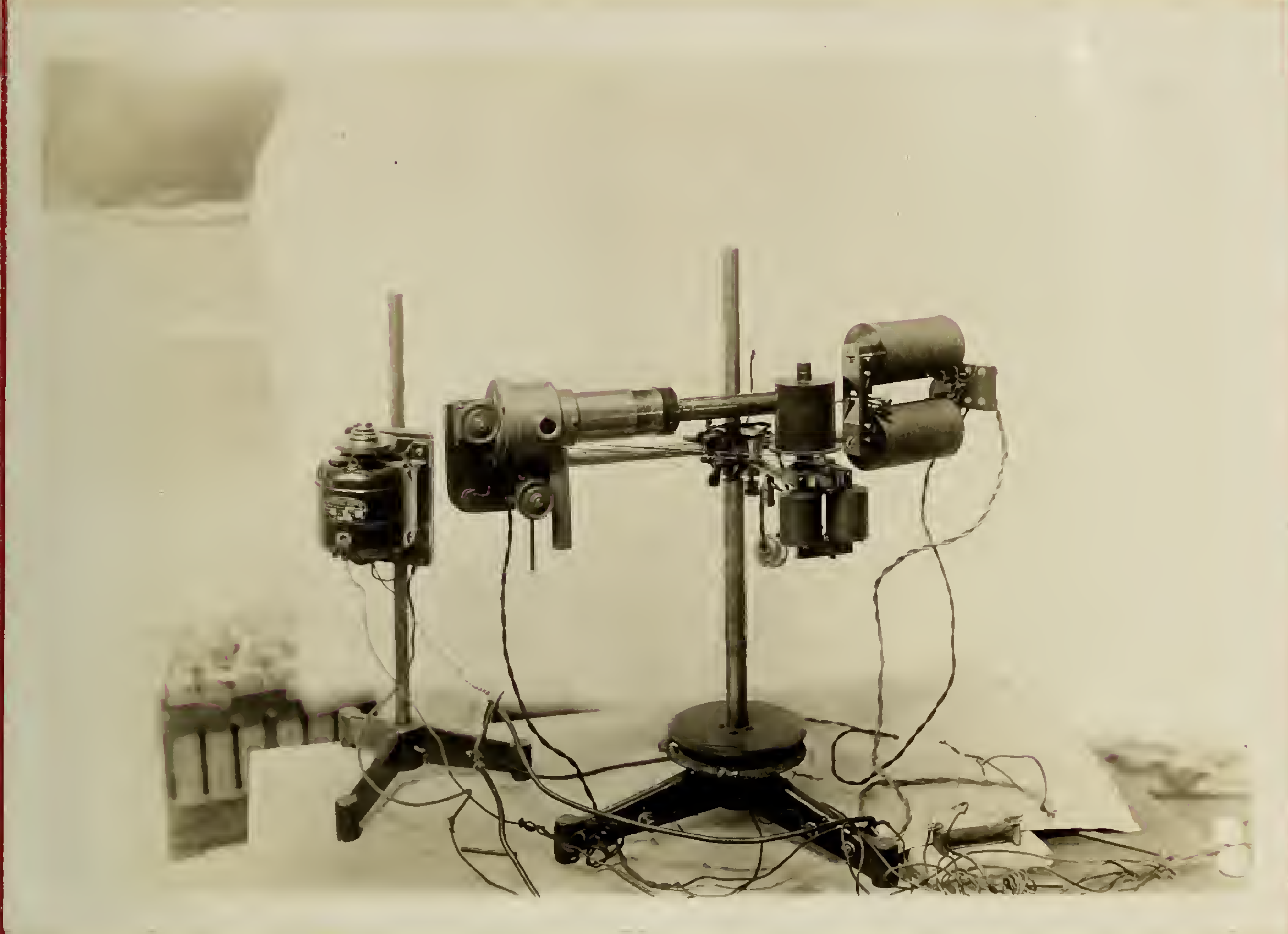
Some of them will be analyzed mathematically by a method described later in an attempt to show what harmonics give the tone its particular character.

II APPARATUS

Various methods have been devised for visualizing and making permanent records of sound waves. One of the first methods was introduced by Koenig and called the manometric flame. This device depended upon the effect of the sound waves upon a rubber diaphragm which in vibrating varied the pressure of gas supplying a burning jet. This variation of pressure caused the flame to change in size which was observed in a system of revolving mirrors which spread the images out in a band.

One of the latest methods is the Phondeik made by Miller of the Case School of Applied Science. This consists of a horn which has a rubber diaphragm stretched across its throat. This vibrating membrane causes a minute mirror to oscillate in one plane. The wave shape is produced by letting a cylinder of mirrors revolve or a photographic negative pass in a plane perpendicular to the mirror oscillations.

The method used in this thesis is an electrical method involving an application of the oscillograph. The preliminary work was done on a type of instrument known as a lecture room oscillograph. This particular instrument was manufactured by H.G. Crane of which a picture is here shown. As may be seen, it consists of four main parts, the arc at the left, the element and field at the extreme right, the revolving mirrors in the center, and the motor for driving them in the rear.



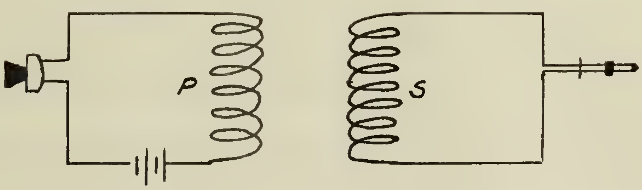
The arc lamp is designed to operate on direct current, using 5 x 250m.m. carbons. For the best results the positive carbon should be cored. About 5 amperes at 110 volts is required to operate the lamp successfully. A pin hole diaphragm allows a small beam of light to pass from the lamp through lenses and fall on the element mirror.

The element is the vital part of the apparatus. It consists of a loop of very fine wire suspended under tension in a strong magnetic field. As current passes through this wire a torsion effect is produced between the magnetic field and the current in the wire. This causes the loop to twist. A mirror which is cemented

to the loop reflects a spot of light which deflects either to one side or the other by an amount proportional to the current in the wire.

The flux is furnished by two large electromagnets. The gap in which the element is placed is very narrow and the pole pieces tapered to concentrate the flux. A special element of finer suspension and higher natural period was used for this work on account of its higher sensitivity.

Since the mirror oscillates in one plane only, a cylinder of mirrors is placed to receive the spot from the element. From these the beam is reflected to a screen. The mirrors on revolving spread out the wave which the eye retains. In order to take advantage of this optical effect each single mirror must reflect its image coincident with the preceding mirror. This necessitates a spread synchronous with the wave produced. A variable speed direct current motor is belted to the mirrors and regulated with hand rheostats to obtain this.



The set-up shown above was found to be the most satisfactory for the work. It consists of a simple circuit of telephone

transmitter, battery, oscillograph element and repeating coil. The latter was found useful in holding the spot of light steady. Since the secondary will have current induced in it only when there is a change in flux, when no sound is being recorded the mirror may remain at a zero deflection instead of a constant deflection due to the normal current such as is flowing in the primary.

The final work of photographing the waves was performed on a General Electric oscillograph with a film attachment and an automatic shutter which exposed the film during one revolution only. This instrument was much more sensitive and accurate than the lecture room instrument.

The analysis of the waves was accomplished by means of the Westinghouse Harmonic Analyzer. All waves analyzed by this machine must be replotted to polar coördinates if a circular oscillogram has not been used. A template of stiff paper is then made of the wave form and fastened on the revolving table of the analyzer. This table has two distinct motions, a backward and forward motion and a rotational motion which are supplied by interchangeable gears.

An arm provided with a tracing point is moved by the template in a perpendicular direction to the linear motion of the table and traveling as a whole with the linear motion. On the opposite end of the arm is fastened the tracing point of a planimeter which integrates the area of the figure described by the two motions. This area divided by the number of the harmonic sought is proportional to the corresponding constant in the Fourier Series. Each harmonic must be found separately with the proper combination of gears. The sine and cosine terms also cannot be taken together but must be obtained by changing the phase of the two motions.

III DATA AND RESULTS

Fig. 1

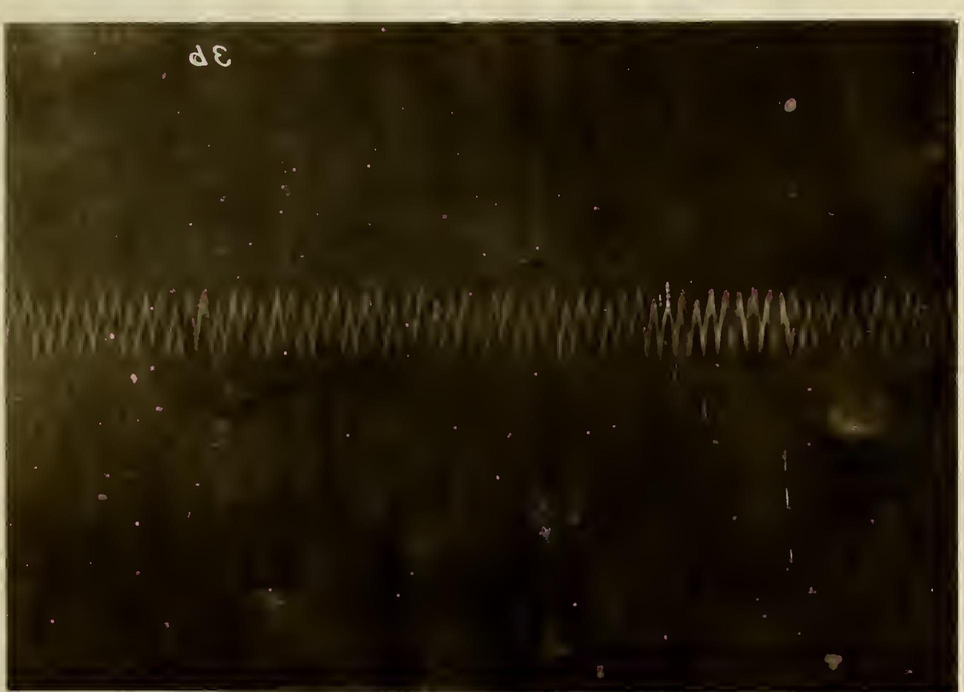


Fig.2

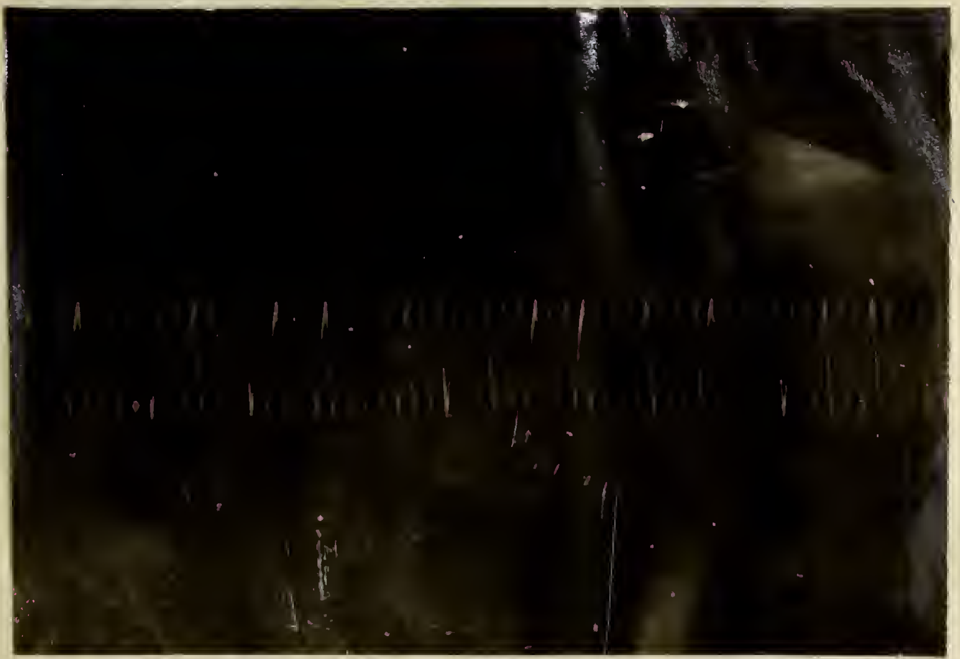


Fig. 3

Sound Waves of an Open Organ Pipe

Fig.1 Fundamental blown softly

Fig.2 Fundamental blown loudly

Fig.3 First overtone.

Analysis of Fig.2

Harmonic	I	II	III	IV
Amplitude	1	1.19	2.72	.495

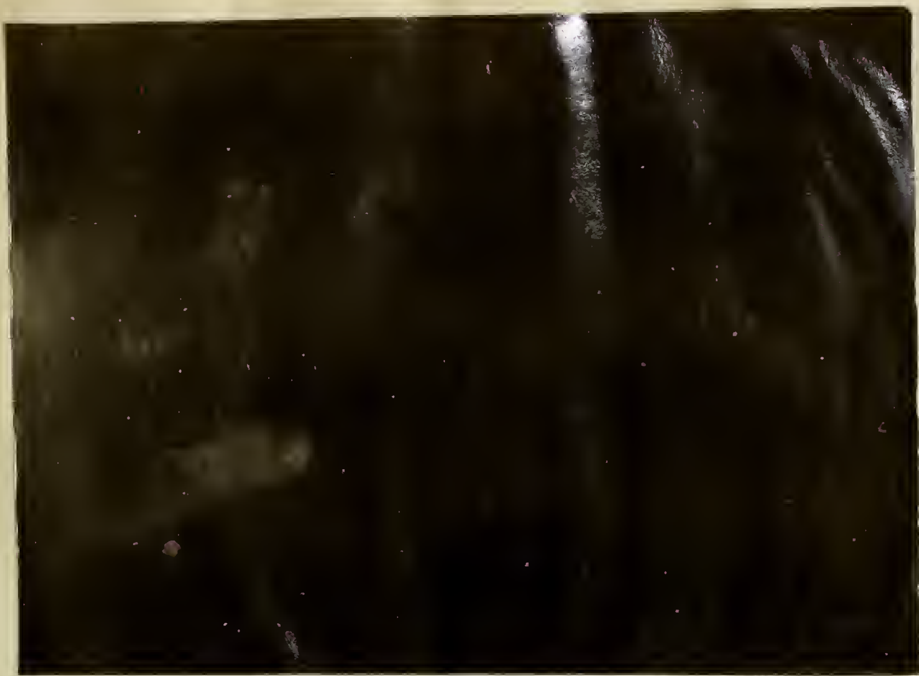


Fig. 4

Tone of the Open G-String of a Pique Violin Bowed Vigorously

Analysis

Harmonic	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Amplitude	1	1.54	.67	.373	4.57	6.6	.97	.685	1.32	.313	.144

Fig. 5

Sound Wave of a Clarinet Playing Low D. (Albert System, A-Clarinet)

Analysis

Harmonic	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Amplitude	1	.795	1.81	1.11	4.75	2.85	7.6	7.78	7.85	4.3	4.3

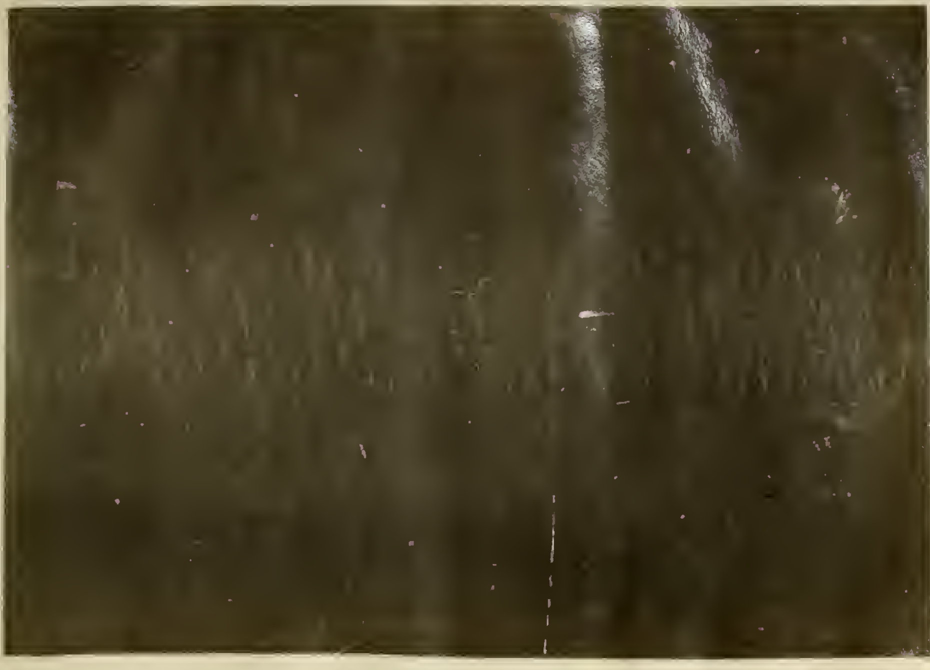


Fig. 6

Sound Wave of Oboe Playing Low B Natural

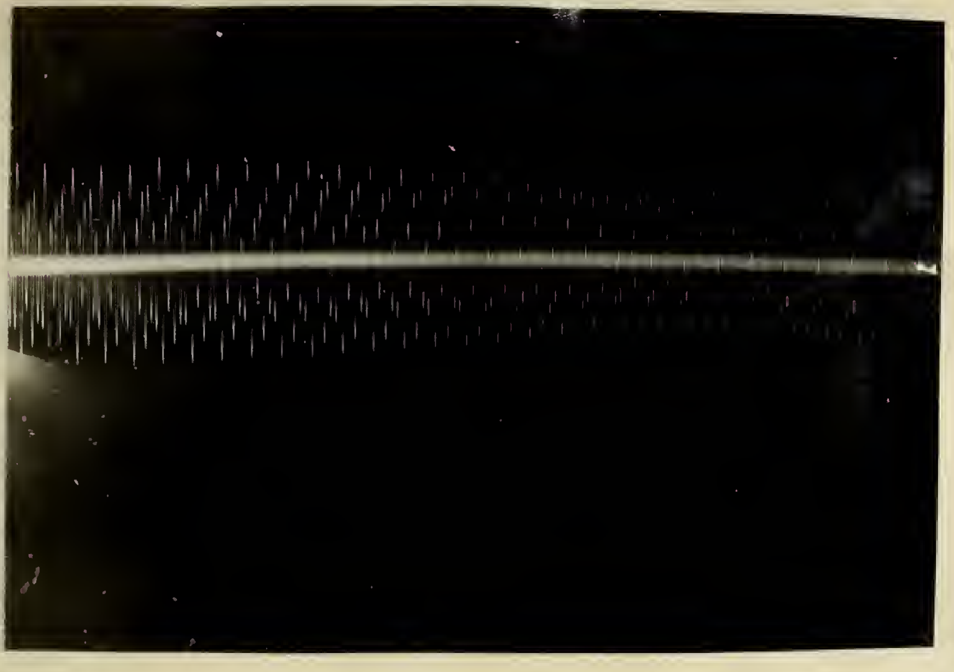


Fig. 8

Sound Wave of a Trained Baritone Voice Singing "ah"

Analysis

Harmonic	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Amplitude	1	.98	1.33	1.71	4.68	.72	.034	.019	.515	[illegible]	.011

Fig. 7

Sound Wave of Untrained Bass Voice Singing the Sound "ah"

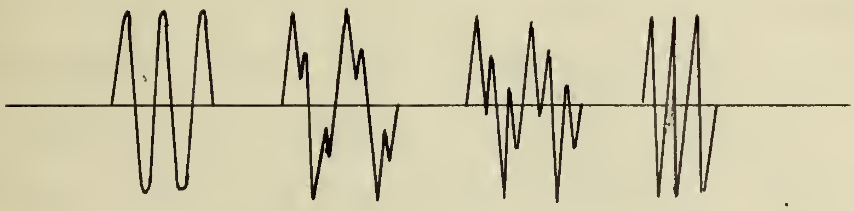
Analysis

Harmonic	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Amplitude	1	1.81	1.03	1.18	3.45	.43	1.41	5.2	1.3	.57	.96

IV CONCLUSIONS

Organ pipes of the type used may be either stopped or open. The former sounding one octave below the latter for a given length. The open pipe only, is considered here. A tone produced by an open pipe is much more brilliant than that produced by a stopped pipe due to the presence of the first harmonic, which may be seen in the analysis. A stopped pipe never has this harmonic, and for this reason its tone is dull.

An interesting change is noted in the character of the open pipe tone as the air pressure is increased. To the average ear, the only change apparent is the change in pitch as the pipe breaks from the fundamental to the first harmonic, or from the first harmonic to the second. The transition, however, is not so sudden as it sounds. The following figure will illustrate the change of wave shape as the fundamental is replaced by the first harmonic.



(a) (b) (c) (d)

Figure (a) represents the tone produced by the pipe when blown very softly. It approaches very closely a simple tone for it is nearly a sine wave. Stages (b) and (c) represent in order, sounds of greater intensity. The notch which appears in (b) has become

deeper in (c). In (d) we find a form which is an easy transition from (c). This is the point which is called the first overtone.

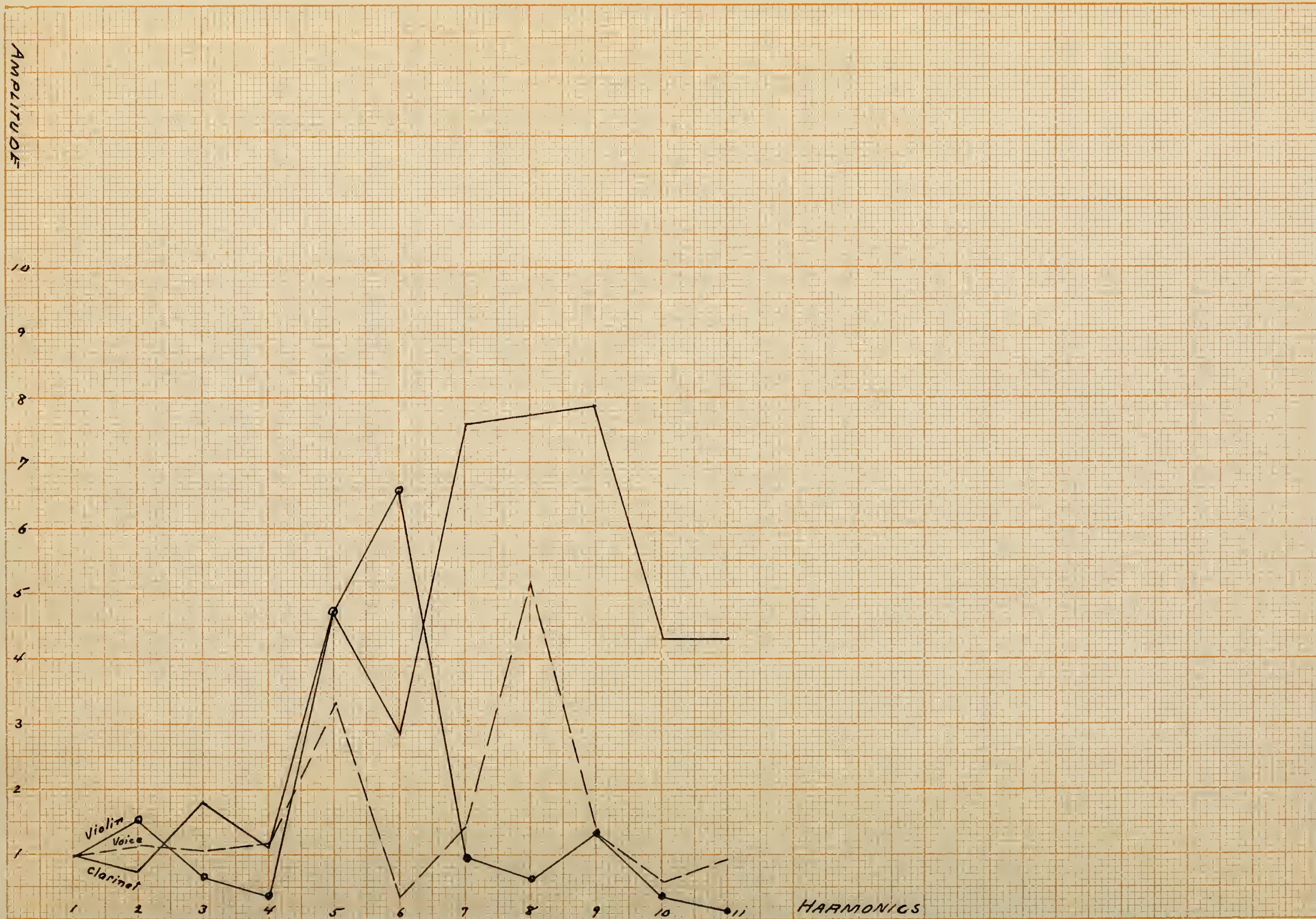
Actual photographs of stage (c) and one between (c) and (d) may be found in the previous chapter, Figures (1) and (2).

The violin, besides being a physically perfect instrument has a further advantage in the matter of tone control. It is one of the very few instruments on which it is possible to vary the harmonics at will. This may be accomplished by varying the pressure and handling of the bow and the point on the string where the bow makes contact. Here is where the personal element enters in tone production and much depends on the skill of the performer.

The note shown in the photograph is of the open G-string. This string being heavier, the quality would be somewhat different than tones from the higher strings. The same note played on different violins would vary considerably due to the particular construction, seasoning and other factors.

From the analysis it is apparent that the fifth and sixth harmonics predominate. All the rest are fairly well represented except the eleventh which is quite small. The instrument used possessed a brilliant tone and was considered rich in harmonics. In taking the photograph the violin was bowed very vigorously, which would tend to increase its brilliancy.

The clarinet and oboe have been chosen as representative of reed instruments. These represent the two classes, the single reed and the double reed. Their reed tones are due to the higher harmonics which are present. Harmonics higher than the sixth and seventh if very strong cause the tone to become sharp and rough. If they are milder the harshness disappears and these harmonics impart a character



AMPLITUDE
10
9
8
7
6
5
4
3
2
1
Violin
Voice
Clarinet
1
2
3
4
5
6
7
8
9
10
11
HARMONICS

and expression to the note which is musically valuable.

Tones containing these harmonics to any great extent are very penetrating. The brass instruments are an example of this. The oboe is perhaps the best example for although it takes the least wind of any wind instrument its tone is the most penetrating.

The wave and analysis given for the clarinet is for D below middle C. An A clarinet was used. To completely represent the instrument it would be necessary to study at least three tones representing the three different registers. Due to the nature of the instrument the quality of the tones in the different registers differs greatly. The A clarinet has a sweeter tone than the B flat instrument although it is not so brilliant.

The voice wave shown is of an untrained bass voice singing the sound "ah". Here the fifth and eighth harmonics appear to predominate. Voice waves would probably show the greatest variation, for a given class, of any wave shown. The variation in voices is much greater than in instruments of any particular kind.

Referring to the curves plotted of the analysis it is interesting to note that of the few tones analysed the clarinet tone most nearly approaches the human voice. In the strictest sense, these values cannot be represented by a continuous curve. The values of the ordinates between the numbered abscissa have no meaning or existance.

This method is not an extremely accurate method of studying harmonics due to the errors introduced in the various steps. The telephone transmitter probably introduces the most errors. They may be of two kinds, (1) distortion due to mouthpiece or horn, and (2) suppression or distortion of harmonics by the diaphragm. Of these two

the latter is probably the more serious.

This trouble is due to the fact that the diaphragm has a distinct natural period of vibration. Whenever a sound is directed towards it of this period there is a resonance effect causing a response of great amplitude. The transmitted electrical waves have to some extent, therefore, the diaphragm characteristics superimposed upon the original sound wave.

The error here introduced may be made minimum by chosing tones as far away from the point of resonance as possible. Practically this is not always easy, for the range of certain instruments includes this point and it is difficult to keep far enough away from it.

The oscillograph element also introduces some slight errors. This may be accounted for by the fact that the element is more sensitive to some frequencies than others, thus exaggerating certain harmonics. These characteristics vary with the tension on the element.

Since the original waves were photographed in rectangular coordinates, it was necessary to replot these waves by hand in polar coordinates to prepare them for analysis by the method previously mentioned. This is somewhat inaccurate at best as the photographed waves are rather small. The harmonic analyzer itself was probably much more accurate than the template prepared in this manner.